Estimation of Atmospheric Attenuation at 99 GHz Using a Total Power Radiometer

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***Abstract*—A total power radiometer operating at 99 GHz was implemented for a propagation experiment aimed to estimate attenuation along a slant path, in Madrid. Valuable data was collected during a measurement campaign in mid-april of 2012. The retrieved time series of radiometric attenuation allow the use of this technique at this frequency to be validated, under clear sky and cloudy conditions, using a low cost instrument calibrated with simple procedures. In spite of some hardware limitations, this experiment shows an interesting application of radiometric technique in order to study atmospheric propagation at 99 GHz.**

I. Introduction

At millimeter frequencies (30-300 GHz), propagation mechanisms through the atmosphere are severely affected by the effects of atmospheric gases, as well as extinction processes caused by liquid water particles found in clouds and rain [1]. Between the gaseous constituents, water vapor exhibit the most important absorption characteristics, within the band, with exception of those frequencies corresponding to oxygen absorption peaks. Under Rayleigh regime, cloud effects can be well estimated by considering that radiation absorption is linearly related to liquid water content [2]. Finally, an accurate approach to estimate extinction caused by rain, due to the combination of absorption and scattering effects, is highly dependent on the drop size distribution during the precipitation. The present paper is mainly concerned with non-precipitating atmosphere scenarios, where attenuation caused by gaseous and clouds is of primary interest.

The use of remote sensing techniques by researchers within the propagation community is broadly extended. The products collected by these instruments constitute valuable data that help to characterize tropospheric channel. A concise review by Crewell [3] summarizes several passive and active sensors currently used by experimenters, among which radiometry has proven to be a useful technique allowing atmospheric absorption along a path to be estimated [4]. In addition, integrated water vapor and liquid water content on a site can also be retrieved by this technique, using a dual-frequency instrument [5].

In a previous work [6], annual statistics of sky brightness temperature, T_b in (K), at 100 GHz were computed using 3-year radiosonde observations (RAOBs) from Madrid/Barajas airport in combination with well established absorption models. One of the most relevant conclusions, extracted from the analysis of the results obtained, is that radiometric estimations of path attenuation at this frequency can be carried out most of the time, with the exception of rainy conditions, in a mid-latitude and continental climate region. As a continuation of these studies, a propagation experiment was carried out using a ground-based single-channel radiometer at 99 GHz.

The present paper is outlined as follows: Section II gives an overview of the experiment; in Section III, a description of the radiometer is presented, and the main processing tasks are briefly discussed. Following, some results of radiometric estimations of atmospheric attenuation during clear sky and cloudy conditions are reported in Section IV, besides a comparison of experimental statistics and estimations based on RAOBs data. At the end of this paper, some conclusions are discussed in Section V.

II. Experiment description

The present experiment was carried out within the framework of the TeraSense project [7], a research initiative supported by the Spanish government, with the aim of increasing the knowledge on the influence of the atmosphere at millimeter and submillimeter frequencies, as well as of developing remote sensing instruments for a variety of applications, including propagation studies.

The implementation of the radiometer is the result of a collaborative work within Universidad Politécnica de Madrid (UPM), involving the GTIC-Radiocommunications Group, and the Radar and Microwave Group (GMR). The instrument is an experimental prototype working at 99 GHz, implemented for the purpose of estimating total attenuation at this frequency along a slant path. It corresponds to a non ad-hoc design, including commercial off-the-shelf (COTS) components and in-house circuits, currently used by the GMR on the prototyping of a security radar system [8], which were temporarily disposed for developing the radiometer.

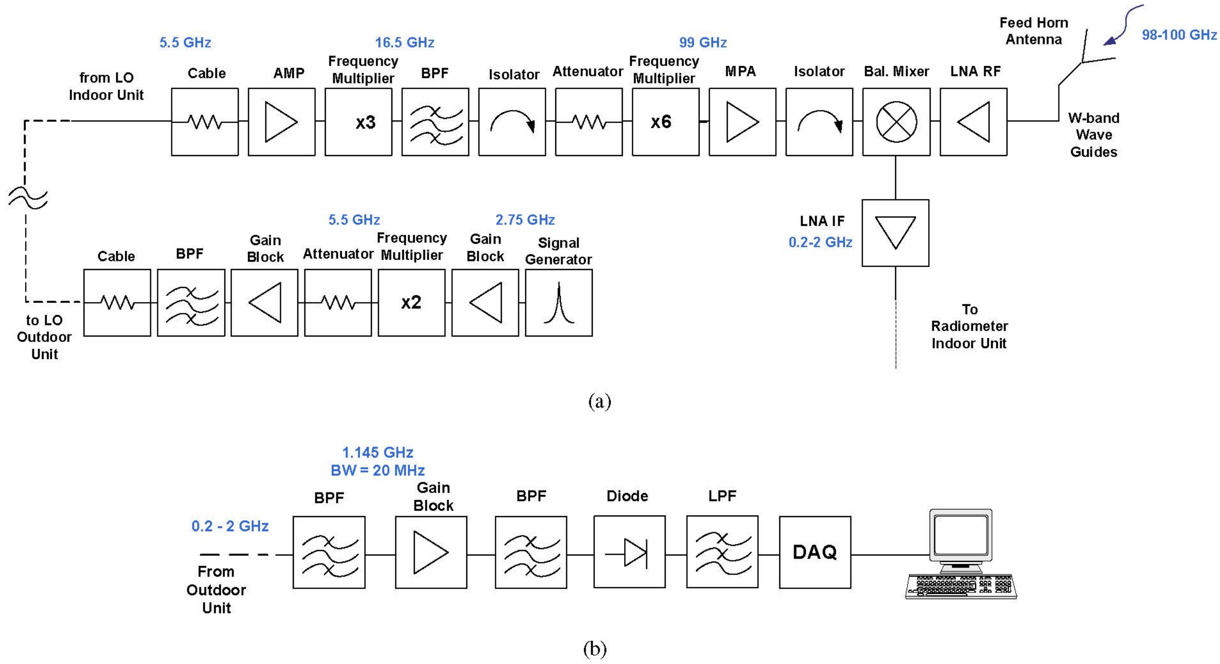


Fig. 1. Block diagrams of 99 GHz radiometer, a) Outdoor Unit, and b) Indoor Unit.

The instrument was installed at UPM facilities located in Madrid (40.45°N, 3.71°W), at an altitude of 660 m above sea level. Madrid is characterized by its continental climate, with hot and dry summers and cold winters. The measurement campaign was performed from April 11th to 24th, 2012. During this period, sky conditions were predominantly characterized by the presence of clouds, being in some cases accompanied by precipitations. In addition, very stable and clear sky scenarios were also observed during a couple of days of the experiment.

On-site monitoring of meteorological conditions was achieved using a co-located weather station recording continuously surface parameters, as well as room and equipment temperatures. Additionally, in presence of precipitation scenarios, 1-min rainfall rate data were obtained from a tipping-bucket rain gauge placed to a few meters of the radiometer, and in some particular cases of light rain, laser disdrometer registers were also checked. Finally, RAOBs carried out twice a day, at local time 00:00 and 12:00 UTC, in Madrid/Barajas Airport (40.45°N, 3.57°W), located at a distance of 14 km of UPM facilities, were also available in order to validate radiometric attenuation measurements.

III. 99 GHz Radiometer

A. Overview

The radiometer is based on a total power receiver, with two well differentiated units. First, an Outdoor Unit (OU), where incoming atmospheric noise is received by a 90-100 GHz conical horn antenna with an elevation angle of approximately 40°. Following, this signal noise is amplified by a W-band LNA and downconverted to IF by a balanced mixer, as it can be seen in Figure 1(a). Mixing process is performed using an LO signal centered at 99 GHz, which is generated by a frequency multiplier circuit (x36) based on three stages, using a 2.75 GHz stable input signal. The design of the multiplier chain includes filtering, amplification and attenuation stages in order to adequate input power levels to the technical specifications of the individual components. In addition, the IF blocks are distributed in the Indoor Unit (IU), where radiometer bandwidth of 20 MHz, centered at a frequency of 1.145 GHz, is defined after a band-pass filtering process. Radiometric voltages at the output of the receiver are obtained after square-law detecting and low pass filtering stages. Figure 1(b) summarizes the main blocks of the IU. Data logging tasks are also included in the IU, in order to register adequate voltage levels, before running pre-processing and processing software routines by an operator.

Gain variations due to thermal effects as well as the value of the receiver system noise, T_{rx} in (K), are critical aspects in radiometers, specially in total power designs, in which output voltage V (V) is given by:

$$V = c(T_b + T_{rx}) \tag{1}$$

where the constant c includes the gain of the receiver as well as other terms as the radiometer bandwidth (more stable) and the Boltzmann constant . In the previous expression, it is assumed, as a first approximation, that atmospheric thermal radiation is detected by the main lobe of the antenna. As a first approximation, side-lobe contributions were considered negligible. A hot-load calibration, placing an absorbing material at ambient temperature in front of the antenna aperture, was carried out approximately each 40-60 min with the perspective of compensate gain instabilities. On the other hand, a first estimation of T_{rx} was achieved by measuring T_b at 99 GHz, at two different elevation angles (i.e. 40° and 90°), in combination with hot-load calibrations. This procedure was implemented on April 24th, during a period of approximately 20 min, where clear sky conditions were observed. After analyzing and processing the voltage series collected at the output of the radiometer during this calibration procedure, a value of $T_{rx} = 735$ K was obtained.

B. Data processing

Radiometric voltages at the output of the receiver were sampled by a Data Acquisition (DAQ) module at a frequency of 60 Hz and then stored as raw data. Pre-processing software routines were then executed with the aim of separating measurements in daily periods, integrating each resulting series with an integration time of 1 s, and removing outliers and bad data. Additionally, hot-load calibration intervals were extracted from every time series. Measurements collected on Sundays, as well as those obtained on night and early morning periods, where there was a long-term absence of hot-load calibrations, were discarded.

During the processing stage, hot-load calibration information was used to convert output voltages corresponding to intervals of atmospheric observation, into sky brightness temperature T_b, and thus estimate the value of the atmospheric attenuation along the path, A_T, given by the following expression, which is valid for a radiometer with an upward-looking observation geometry:

$$A_T = 10 \log \frac{T_{mr} - T_0}{T_{mr} - T_b} \tag{2}$$

where the mean radiating temperature, T_{mr} in K, was estimated by the equation (3), obtained from an exhaustive analysis of meteorological data of Madrid/Barajas airport [9]:

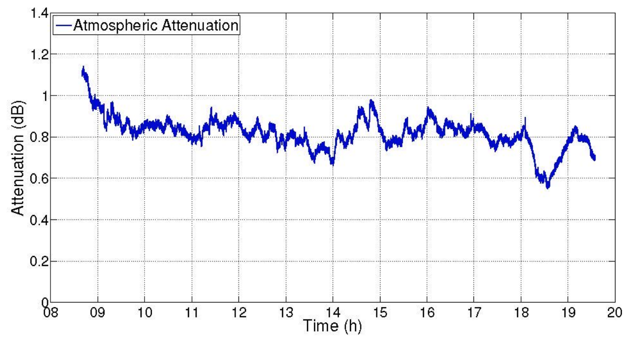
$$T_{mr} = 1.0833 T_{surf} - 24.7784 \tag{3}$$

where T_{surf} in K, is the surface temperature registered by the weather station. The parameter T_0 in (2) is the cosmic background temperature, whose value is equal to 2.736 K. In practice, the correct applicability of (2) is reduced to the case of low attenuation conditions and non-scattering scenarios, assuming local thermodynamic equilibrium conditions for the troposphere.

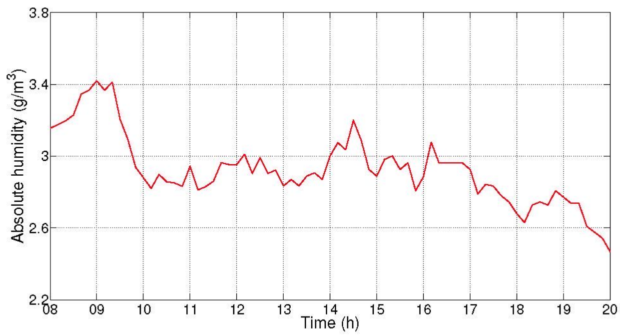
IV. Results

In the following paragraphs, some representative propagation scenarios during the campaign are examined, such as the presence of clear sky and clouds. Radiometric estimations of A_T are represented in order to illustrate the effects of the medium conditions during each particular observation period.

Additionally, estimation of A_T along a slant path of 40°, expressed as the sum of absorption caused by gases and clouds, under the assumption of Rayleigh regime, were computed from height profiles of temperature, pressure and water vapor collected by RAOBs, with the purpose of comparing with experimental results. The ITU-R Rec. P.676 [10] and Salonen model [11], respectively, were used in order to estimate absorption levels corresponding to each set of meteorological profiles.



(a)



(b)

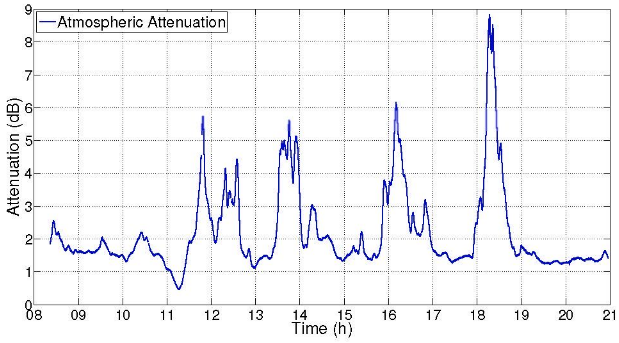
Fig. 2. Measurements during clear sky conditions on April 16th : a) atmospheric attenuation at 99 GHz, and b) surface absolute humidity.

A. Clear sky event

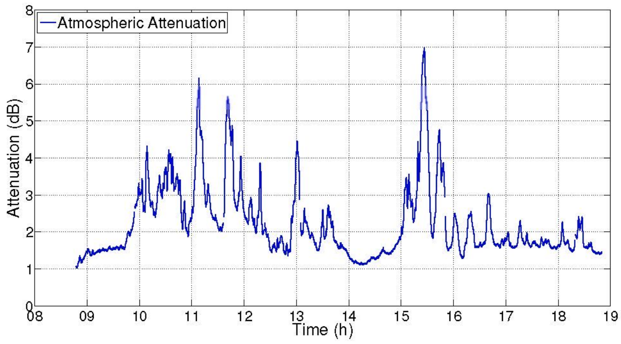
An example of measurements of A_T during clear sky conditions can be observed in Fig. 2(a). It corresponds to an 11-h period, approximately comprised between 08:30 and 19:30, for the day of 16th April. The most relevant feature observed during this dry period is the small range of variation of surface absolute humidity, as it can be seen in Fig. 2(b), where maximum and minimum values are $3.4\ \mathrm{g/m^3}$ and $2.6\ \mathrm{g/m^3}$, respectively. Besides, after examining registers corresponding to other days, it can be verified that these values of water vapor concentration are among the lowest observed during the whole campaign.

Attenuation levels measured by the radiometer are comprised between 0.6 and 1.1 dB, with a relatively stable behavior suggesting that gain fluctuations of the receiver have been compensated by hot-load calibrations. After analyzing Figs. 2(a) and 2(b), it can be noticed a very good degree of correlation between both measurements: the first one characterizing the entire atmospheric profile and the second one corresponding to a surface parameter. As it can be seen, variations show similar behaviors, especially during those short periods where local maximum and minimum values are observed.

The corresponding value of attenuation estimated from RAOB at 13:00 (12:00 UTC), in Madrid/Barajas, is about 0.7



(a)



(b)

Fig. 3. Measurements of attenuation at 99 GHz under the presence of clouds: a) April 12th , and b) April 20th .

dB. Within a reasonable interval of time around the radiosonde launching time, it can be observed that radiometric estimation is slightly larger. However, this difference does not exceed 0.1 dB.

B. Cloudy events

Figs. 3(a) and 3(b) represent radiometric measurements of A_T corresponding to April 12th and 20th , respectively. Both days featured permanent cloudiness, associated to low altitude and stratified clouds, along the intervals of time where valid radiometric data were gathered. Additionally, the sporadic presence of light drizzle of short duration was instantaneously detected on surface by the co-site laser disdrometer, with peak values of rain intensity below to 1.5 mm/h. These events were more frequent during April 20th.

The high sensitivity of the radiometer to the presence of liquid water in the atmosphere is certainly verified after a visual inspection of the two time series. The range of variability of atmospheric attenuation is comprised between approximately 1.5 dB and 9 dB. It must be pointed out that several peaks observed in both Fig. 3(a) and 3(b) correspond to the presence of water particles described in the previous paragraph. Notwithstanding this isolated events, the most part of the high variability is closely related to the effect of liquid water into clouds. As it can be observed during the periods of time comprised between 11:00 and 16:00 in April 12th , or between 15:00 and 19:00 in April 20th , where neither the rain gauge nor the disdrometer register the presence of water droplets, the attenuation measured by the radiometer can reach values of up to almost 7 dB.

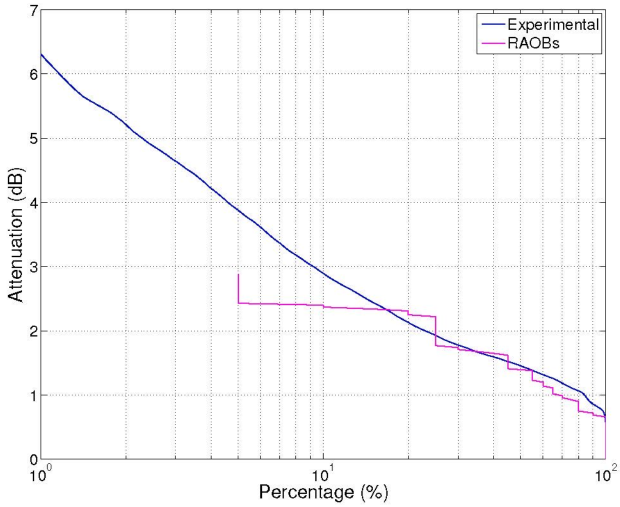


Fig. 4. Comparison of atmospheric attenuation at 99 GHz measured by the radiometer and estimated by RAOBs

It is equally important to note on the presence of a reference attenuation level on the measurements. It is expected that after the passage of clouds with high liquid water content, the radiometer measurement tends to reach a stable reference level. As it can be verified from the inspection of the two time series, this level is comprised between 1.1 and 1.5 dB. In a similar way as at the observed under clear sky conditions, this behavior suggests that gain receiver variations along the day are compensated by the calibration procedure implemented. This observation can be considered as a valuable demonstration of the good performance of the radiometer under cloud scenarios.

Predicted value of A_T from RAOBs in Madrid/Barajas at 13:00 on April 12th is 1.7 dB, and 2.3 dB, at the same time, on April 20th . Experimental values measured at our site, approximately at the same time, are reasonably in agreement with these estimations based on vertical meteorological profiles. It has to be taken into account that this comparison gives only a first idea about the relative accuracy of the measurement with our instrument, because of the temporal and spatial variability of clouds, in some cases accompanied by precipitations, on both sites.

C. Comparison between measurements and RAOBs estimations

The last part of this study is devoted to compare the total amount of measurements of A_T registered by the radiometer with estimations based on those RAOBs carried out during the experimental campaign. A total of approximately 103 h of radiometric data and 20 RAOBs, not carried out during precipitation conditions [12], were considered in this analysis. This comparison is performed in terms of complementary cumulative distributions functions (CCDFs), which were computed and plotted in Fig. 4.

Due to the small number of RAOBs available within the period under study, the resulting CCDF features a discretized behavior and the comparison with the experimental CCDF can not be accomplished for the same percentages of time. However, as it can be verified from the results obtained, there is a relatively good agreement between both cumulative statistics. From a quantitative point of view, even though some slight differences are observed, it can be concluded that experimental measurements are very close to the values estimated from prediction models.

V. Conclusions

In this paper we have described a low cost radiometer at 99 GHz, which has been used in a short-term propagation experiment. The main purpose of this deployment was to allow atmospheric attenuation at this frequency to be retrieved from sky brightness temperature measurements.

Some of the key results of this pilot experience at UPM are as follows:

- Attenuation at 99 GHz can be estimated by radiometric measurements, especially during clear sky and cloudy conditions. It has been verified that measurements are in agreement with estimations based on calculations using vertical meteorological profiles and propagation models.
- Therefore, this radiometric retrieval technique of total attenuation has been validated at 99 GHz during a spring period, in a mid-latitude and continental climate as Madrid.
- Finally, the great sensitivity of the 99 GHz-channel to the presence of liquid water along the atmospheric path observed by the radiometer, has been clearly verified. This is one of the most important characteristics of implementing a radiometer at this frequency or similar ones.

Future lines of work of the present study are related to the development of a new radiometric campaign during a different period of the year, characterized by different meteorological conditions. Moreover, following the collaborative work with the GMR, the implementation of active remote sensing instruments at 99 GHz or above is foreseen , as well as the investigation of their use in propagation experiments.

Acknowledgment

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